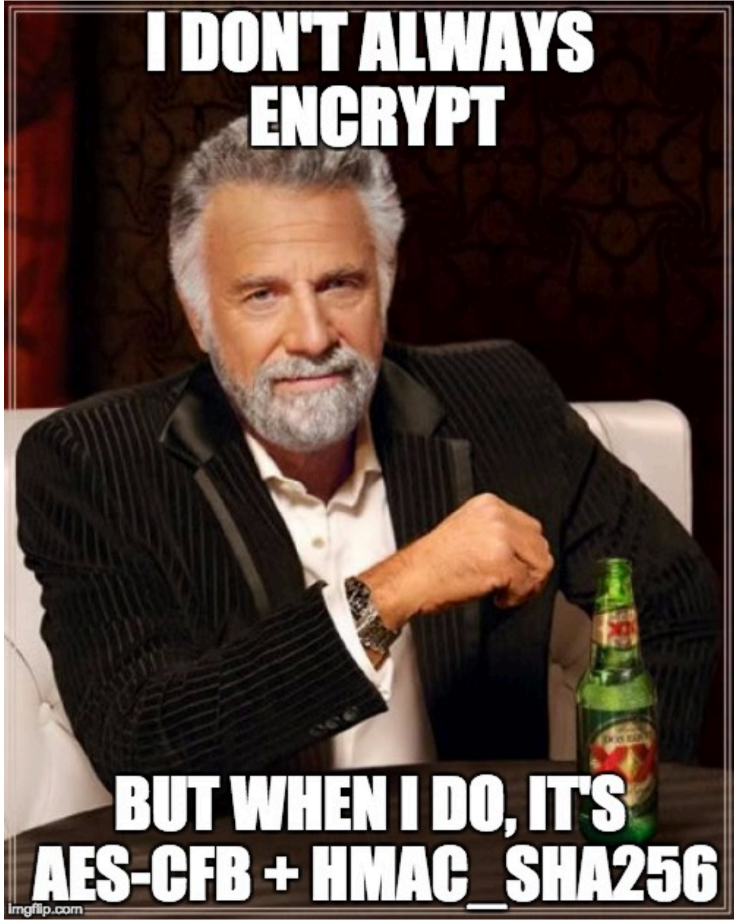
Integrity, Hashes, & "Random" Numbers



Mallory the Manipulator

- Mallory is an active attacker
  - Can introduce new messages (ciphertext)
  - Can “replay” previous ciphertexts
  - Can cause messages to be reordered or discarded
- A “Man in the Middle” (MITM) attacker
  - Can be much more powerful than just eavesdropping

Encryption Does Not Provide Integrity

- Simple example: Consider a block cipher in CTR mode...
- Suppose Mallory knows that Alice sends to Bob “Pay Mal $0100”. Mallory intercepts corresponding C
  - M = “Pay Mal $0100”. C = “r4ZC#jj8qThMK”
  - $M_{10..13}$ = “0100”. $C_{10..13}$ = “ThMK”
- Mallory wants to replace some bits of C...

Encryption Does Not Provide Integrity

- Mallory computes
  - “0100” $\oplus$ $C_{10..13}$
    - Tells Mallory that section of the counter XOR: Remember that CTR mode computes $E_k(IV||CTR)$ and XORs it with the corresponding part of the message
  - $C'_{10..13}$ = "9999" $\oplus$ “0100” $\oplus$ $C_{10..13}$
- Mallory now forwards to Bob a full $C' = C_{0..9}||C'_{10..13}||C_{14...}$
- Bob will decrypt the message as "Pay Mal $9999"...
  - For a CTR mode cipher, Mallory can in general replace any ***known*** message M with a message M' of equal length!

Integrity and Authentication

- Integrity: Bob can confirm that what he's received is exactly the message M that was originally sent
- Authentication: Bob can confirm that what he's received was indeed generated by Alice
- Reminder: for either, confidentiality may-or-may-not matter
  - E.g. conf. not needed when Mozilla distributes a new Firefox binary
- Approach using symmetric-key cryptography:
  - Integrity via MACs (which use a shared secret key **K**)
  - Authentication arises due to confidence that only Alice & Bob have **K**
- Approach using public-key cryptography (later on):
  - "Digital signatures" provide both integrity & authentication together
- Key building block: cryptographically strong hash functions

Hash Functions

- Properties
  - Variable input size
  - Fixed output size (e.g., 256 bits)
  - Efficient to compute
  - Pseudo-random (mixes up input extremely well)

- Provides a “fingerprint” of a document
  - E.g. “**`shasum -a 256 <exams/mt1-solutions.pdf`**” prints **`0843b3802601c848f73ccb5013afa2d5c4d424a6ef477890ebf8db9bc4f7d13d`**

Cryptographically Strong Hash Functions

- A collision occurs if **x≠y** but **Hash(x) = Hash(y)**
  - Since input size > output size, collisions do happen
- A cryptographically strong **Hash(x)** provides three properties:
  - One-way: **h = Hash(x)** easy to compute, but not to invert.
    - Intractable to find ***any*** **x'** s.t. **Hash(x') = h**, for a given **h**
    - Also termed “preimage resistant”

H(🐮) =

Cryptographically Strong Hash Functions

- The other two properties of a cryptographically strong **Hash(x)**:
    - Second preimage resistant: given **x**, intractable to find **x'** s.t. **Hash(x) = Hash(x')**
    - Collision resistant: intractable to find any **x**, **y** s.t. **Hash(x)** = **Hash(y)**
- Collision resistant ⟹ Second preimage resistant
    - We consider them separately because given Hash might differ in how well it resists each
    - Also, the Birthday Paradox means that for n-bit Hash, finding **x-y** pair takes only ≈ $\mathbf{2^{n/2}}$ pairs
        - Vs. potentially $\mathbf{2^n}$ tries for **x'**: **Hash(x) = Hash(x')** for given **x**

Cryptographically Strong Hash Functions, con't

- Some contemporary hash functions
  - MD5: 128 bits
    - broken – lack of collision resistance
    - Collisions for the heck of it: https://shells.aachen.ccc.de/~spq/md5.gif
      An MD5 "hash quine": an animated GIF that shows its own hash
  - SHA-1: 160 bits broken (as of spring 2017, but was known to be weak yet still used...)
  - SHA-256/SHA-384/SHA-512: 256, 384, 512 bits in the SHA-2 family, at least not currently broken
  - SHA-3: New standard! Yayyy!!!! (Based on Keccak, again 256b, 384b, and 512b options)
- Provide a handy way to unambiguously refer to large documents
  - If hash can be securely communicated, provides integrity
    - E.g. Mozilla securely publishes SHA-256(new FF binary)
    - Anyone who fetches binary can use "`cat binary | shasum -a 256`" to confirm it's the right one, untampered
- Not enough by themselves for integrity, since functions are completely known – Mallory can just compute revised hash value to go with altered message

SHA-256...

- SHA-256/SHA-384 are two parameters for the SHA-2 hash algorithm, returning 256b or 384b hashes
  - Works on blocks with a truncation routine to make it act on sequences of arbitrary length
- Is vulnerable to a ***length-extension attack***: **s** is secret
  - Mallory knows **len(s)**, **H(s)**
  - Mallory can use this to calculate **H(s||M)** for an **M** of Mallory's construction
    - Works because ***all the internal state*** at the point of calculating **H(s||...)** is derivable from **H(s)** and **len(s)**
- New SHA-3 standard (Keccak) does not have this property

Stupid Hash Tricks: Sample A File...

- BlackHat Dude claims to have 150M records stolen from Equifax...
  - How can I as a reporter verify this?
- Idea: If I can have the hacker select 10 ***random*** lines...
  - And in selecting them also say something about the size of the file...
  - Voila! Verify those lines and I now know he's not full of BS
- Can I use hashing to write a small script which the BlackHat Dude can run?
  - Where I can easily verify that the 10 lines were sampled at random, and can't be faked?

Sample a File

```
#!/usr/bin/env python
import hashlib, sys
hashes = {}

for line in sys.stdin:
    line = line.strip()
    for x in range(10):
        tmp = "%s-%i" % (line, x)
        hashval = hashlib.sha256(tmp)
        h = hashval.digest()
        if x not in hashes or hashes[x][0] > h:
            hashes[x] = (h, hashval, tmp)

for x in range(10):
    h, hashval, val = hashes[x]
    print "%s=\"%s\"" % (hashval.hexdigest(), val)
```

Why does this work?

- For each x in range 0-9...
  - Calculates **H(line||x)**
  - Stores the lowest hash matching so far
- Since the hash appears random...
  - Each iteration is an independent sample from the file
  - The expected value of H(line||x) is a function of the size of the file: More lines, and the value is smaller
- To fake it...
  - Would need to generate fake lines, ***and see if the hash is suitably low***
  - Yet would need to make sure these fake lines semantically match!
    - Thus you can't just go "John Q Fake", "John Q Fakke", "Fake, John Q", etc...

Message Authentication Codes (MACs)

- Symmetric-key approach for integrity
  - Uses a shared (secret) key **K**
- Goal: when Bob receives a message, can confidently determine it hasn't been altered
  - In addition, whomever sent it must have possessed **K**
    (⇒ message authentication, sorta…)
- Conceptual approach:
  - Alice sends **{M, T}** to Bob, with tag **T = MAC(K, M)**
    - Note, **M** could instead be **C = E_K'(M)**, but not required
  - When Bob receives **{M', T'}**, Bob checks whether **T' = MAC(K, M')**
    - If so, Bob concludes message untampered, came from Alice
    - If not, Bob discards message as tampered/corrupted

Requirements for Secure MAC Functions

- Suppose MITM attacker Mallory intercepts Alice's **{M, T}** transmission …
  - … and wants to replace **M** with altered **M***
  - … but doesn't know shared secret key **K**
- We have secure integrity if MAC function **T = MAC(M, K)** has two properties:
  - Mallory can't compute **T* = MAC(M*, K)**
    - Otherwise, could send Bob **{M*, T*}** and fool him
  - Mallory can't find **M**** such that **MAC(M**, K) = T**
    - Otherwise, could send Bob **{M**, T}** and fool him
- These need to hold even if Mallory can observe many **{M_i, T_i}** pairs, including for **M_i**'s she chose

MAC then Encrypt or Encrypt then MAC

- You should ***never*** use the same key for the MAC and the Encryption
  - Some MACs will break completely if you reuse the key
  - Even if it is ***probably*** safe (eg, AES for encryption, HMAC for MAC) its still a bad idea
- MAC then Encrypt:
  - Compute **T = MAC(M,K_{mac})**, send **C = E(M||T,$K_{encrypt}$)**
- Encrypt then MAC:
  - Compute **C = E(M,$K_{encrypt}$)**, **T = MAC(M,K_{mac})**, send **C||T**
- Theoretically they are the same, but...
  - Once again, its time for ...

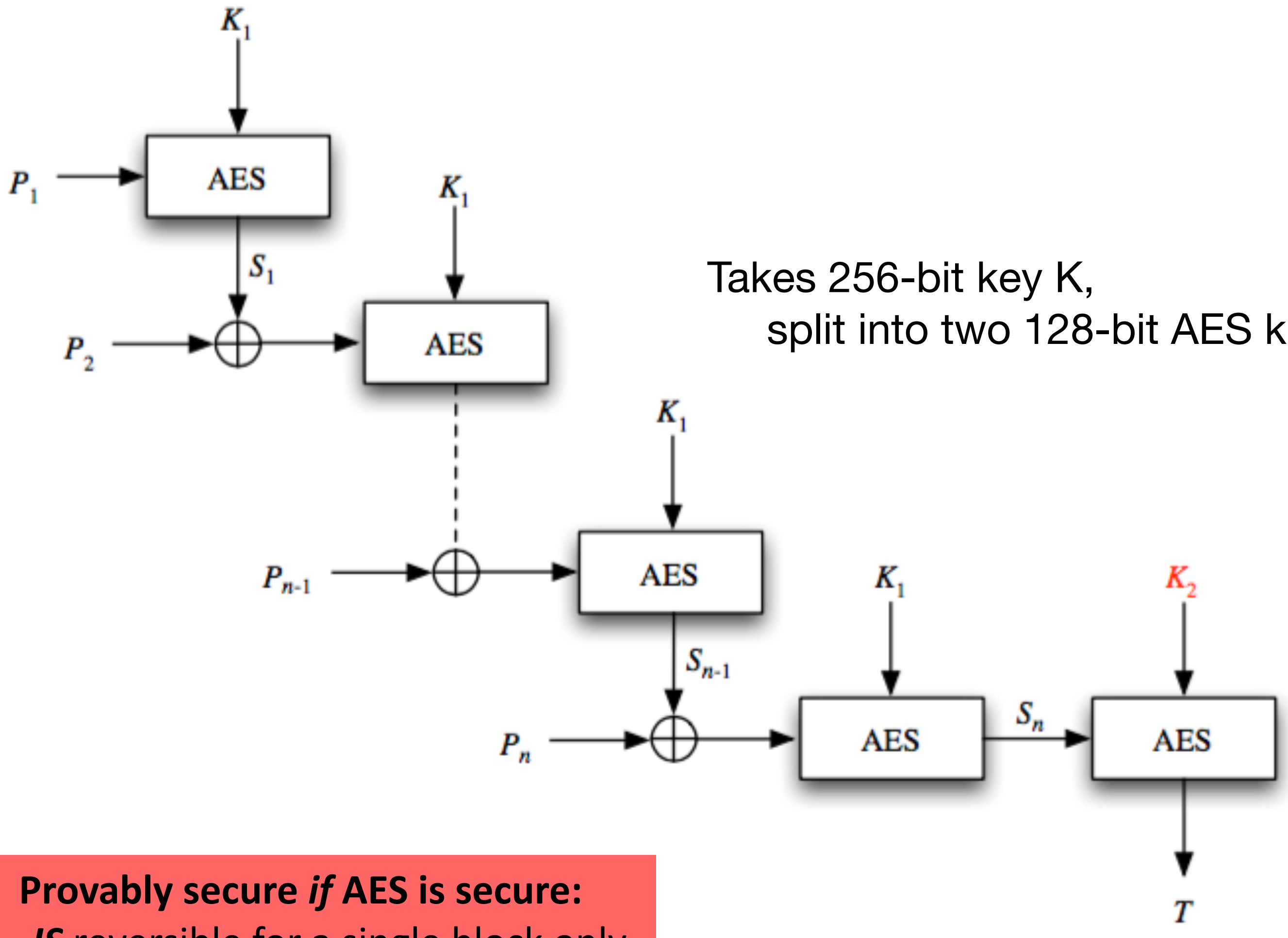
HTTPS Authentication in Practice

- When you log into a web site, it sets a "cookie" in your browser
  - All subsequent requests include this cookie so the web server knows who you are
- If an attacker can get your cookie...
  - They can impersonate you on the "Secure" site
- And the attacker can create multiple tries
  - On a WiFi network, inject a bit of JavaScript that repeatedly connects to the site
  - While as a man-in-the-middle to manipulate connections

The TLS 1.0 "Lucky13" Attack: "F-U, This is Cryptography"

- HTTPS/TLS uses MAC then Encrypt
  - With CBC encryption
- The Lucky13 attack changes the cipher text in an attempt to discover the state of a byte
  - But can't predict the MAC
  - The TLS connection retries after each failure so the attacker can try multiple times
    - Goal is to determine the status each byte in the authentication cookie which is in a known position
- It detects the ***timing*** of the error response
  - Which is different if the guess is right or wrong
    - Even though the underlying algorithm was "***proved***" secure!
- So always do Encrypt then MAC since, once again, it is more mistake tolerant

AES-EMAC: Building a MAC out of a secure block cipher



Takes 256-bit key K,
split into two 128-bit AES keys, K_1 and K_2

Provably secure *if* AES is secure:
IS reversible for a single block only

The best MAC construction: HMAC

- Idea is to turn a hash function into a MAC
  - Since hash functions are often much faster than encryption
  - While still maintaining the properties of being a cryptographic hash
- Reduce/expand the key to a single hash block
- XOR the key with the i_pad
  - 0x363636... (one hash block long)
- Hash ((K ⊕ i_pad) || message)
- XOR the key with the o_pad
  - 0x5c5c5c...
- Hash ((K ⊕ o_pad) || first hash)

```
function hmac (key, message) {
    if (length(key) > blocksize) {
        key = hash(key)
    }
    while (length(key) < blocksize) {
       key = key || 0x00
    }
    o_key_pad = 0x5c5c... ⊕ key
    i_key_pad = 0x3636... ⊕ key
    return hash(o_key_pad ||
                hash(i_key_pad || message))
}
```

Why This Structure?

- i_pad and o_pad are slightly arbitrary
  - But it is necessary for security for the two values to be different
    - So for paranoia chose very different bit patterns
- Second hash prevents appending data
  - Otherwise attacker could add more to the message and the HMAC and it would still be a valid HMAC for the key
    - Wouldn't be a problem with the key at the ***end*** but at the start makes it easier to capture intermediate HMACs
- Is a Pseudo Random Function if the underlying hash is a PRF
  - AKA if you can break this, you can break the hash!

```
function hmac (key, message) {
    if (length(key) > blocksize) {
        key = hash(key)
    }
    while (length(key) < blocksize) {
       key = key || 0x00
    }
    o_key_pad = 0x5c5c... ⊕ key
    i_key_pad = 0x3636... ⊕ key
    return hash(o_key_pad ||
                hash(i_key_pad || message))
}
```

Great Properties of HMAC...

- It is still a hash function!
  - So all the good things of a cryptographic hash:
    An attacker or even the recipient shouldn't be able to calculate **M** given **HMAC(M,K)**
  - An attacker who doesn't know **K** can't even verify if **HMAC(M,K) == M**
    - Very different from the hash alone, and potentially very useful:
      Attacker can't even brute force try to find **M** based on **HMAC(M,K)**!
- Its probably safe if you screw up and use the same key for both MAC and Encrypt
  - Since it is a different algorithm than the encryption function...
  - ***But you shouldn't do this anyway***!

Considerations when using MACs

- Along with messages, can use for data at rest
  - E.g. laptop left in hotel, providing you don’t store the key on the laptop
  - Can build an efficient data structure for this that doesn’t require re-MAC’ing over entire disk image when just a few files change
- MACs in general provide no promise not to leak info about message
  - Though the ones we've seen don't if the key is secret
  - Compute MAC on ciphertext if this matters
  - Or just use HMAC, which ***does*** promise not to leak info if the underlying hash function doesn't
- ***NEVER*** use the same key for MAC and Encryption...
  - Known "FU-this-is-crypto" scenarios reusing an encryption key for MAC in some algorithms when its the same underlying block cipher for both

Passwords

- The password problem:
    - User Alice authenticates herself with a password ***P***
- How does the site verify later that Alice knows ***P***?
- Classic:
    - Just store {**Alice,** ***P***} in a file...
- But what happens when the site is hacked?
    - The attacker now knows Alice's password!
- Enter "Password Hashing"

Password Hashing

- Instead of storing {**Alice, *P***}...
  - Store {**Alice, H(*P*)**}
- To verify Alice, when she presents ***P***
  - Compute **H(*P*)** and compare it with the stored value
- Problem: Brute Force tables...
  - Most people chose bad passwords...
    And these passwords are known
  - Bad guy has a huge file...
    - **H(P1), P1**
      H(P2), P2
      H(P3), P3...
  - Ways to make this more efficient ("Rainbow Tables")

A Sprinkle of Salt...

- Instead of storing {**Alice, H(P)**}, also have a user-specific string, the "Salt"
  - Now store {**Alice, Salt, H(P||Salt)**}
  - The salt ideally should be both long and random, but it isn't considered "secret"
- As long as the salt is unique...
  - An attacker who captures the password file has to ***brute force*** Alice's password on its own
- Its still an "off-line attack" (Attacker can do all the computation he wants) but...
  - At least the attacker can't ***precompute*** possible solutions

Slower Hashes...

- Most cryptographic hashes are designed to be ***fast***
  - After all, that is the point: they should not only turn **H(🐮)** to hamburger... they need to do it quickly
- But for password hashes, we ***want*** it to be slow!
  - Its OK if it takes a good fraction of a second to ***check*** a password
    - Since you only need to do it once for each legitimate usage of that password
  - But the attacker needs to do it for each password he wants to try
- Slower hashes don't change the ***asymptotic difficulty*** of password cracking but can have huge practical impact
  - Slow rate by a factor of 10,000 or more!

PBKDF2

- "Password Based Key Derivation Function 2"
  - Designed to produce a long "random" bitstream derived from the password
- Used for both a password hash and to generate keys derived from a user's password
  - PKBDF(PRF, P, S, c, len):
    - **PRF** == Pseudo Random Function (e.g. HMAC-SHA256)
    - **P** == Password
    - **S** == Salt
    - **c** == Iteration count
    - **len** == Number of bits/bytes requested
    - **DK** == Derived Key

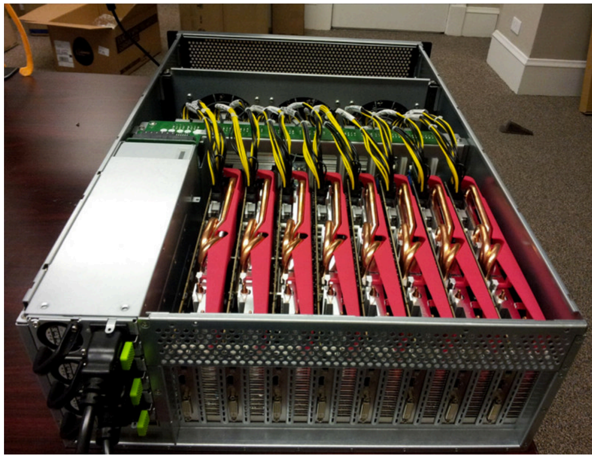
```
PKBDF(PRF,P,S,c,len){
  DK = ""
  for i = 1,range(len/blocksize)+1){
    DK = DK || F(PRF,P,S,c,i)
  }
  return DK[0:len]
}

F(PRF,P,S,c,i){
  UR = U = PRF(P, S||INT_32(i))
  for j = 2; j <= c; ++j {
    U = PRF(P, U)
    UR = UR ^ U
  }
  return UR
}
```

Comments on PBKDF2

- Allows you to get effectively an arbitrary long string from a password
  - ***Assuming*** the user's password is strong/high entropy
- Very good for getting a bunch of symmetric keys from a single password
  - You can also use this to seed a pRNG for generating a "random" public/private key pair
- Designed to be slow in computation...
  - But it does ***not*** require a lot of memory:
    Other functions are also expensive in memory as well, e.g. scrypt.

Passwords...

- If an attacker can do an ***offline*** attack, your password must be ***really good***
  - Attacker simply tries a huge number of passwords in parallel using a GPU-based computer
  - So you need a ***high entropy*** password:
    - Even xkcd-style is only 10b/word, so need a 7 or more ***random word*** passphrase to resist a determined attacker
- Life is far better is if the attacker can only do ***online*** attacks:
  - Query the device and see if it works
  - Now limited to a few tries per second and ***no parallelism!***



... and iPhones

- Apple's security philosophy:
  - In your hands, the phone should be everything
  - In anybody else's, it should (ideally) be an inert "brick"
- Apple uses a small co-processor in the phone to handle the cryptography
  - The "Secure Enclave"
- The rest of the phone is untrusted
  - Notably the memory: ***All*** data must be encrypted:
    The CPU requests that the Secure Enclave unencrypt data and some data (e.g., your credit card for ApplePay) is only readable by the Secure Enclave
- They also have an ability to effectively erase a small piece of memory
  - "Effaceable Storage": this takes a good amount of EE trickery

Crypto and the iPhone Filesystem

- A lot of keys encrypted by keys...
  - But there is a random master key, $\mathbf{k}_{\mathbf{phone}}$, that is the root of all the other keys
- Need to store $\mathbf{k}_{\mathbf{phone}}$ encrypted by the user's password in the flash memory
  - PBKDF2(P,...) = $\mathbf{k}_{\mathbf{user}}$
- But how to prevent an off-line brute-force attack?
  - Also have a 256b ***random*** secret burned into the Secure Enclave
    - Need to take apart the chip to get this!
- Now the user key is not just a function of P, but P||secret
  - Without the secret, ***can not*** do an offline attack
- All ***online*** attacks have to go through the secure enclave
  - After 5 tries, starts to slow down
  - After 10 tries, can (optionally) nuke $\mathbf{k}_{\mathbf{phone}}$!
    - Erase just that part of memory -> effectively erases the entire phone!

Backups...

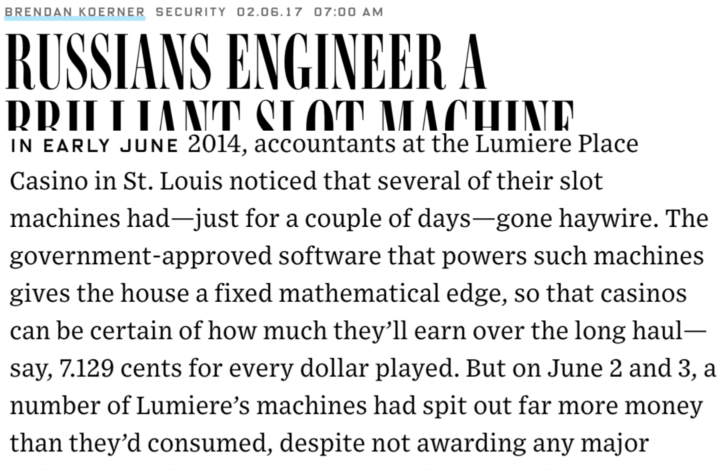
- Of course there is a ***necessary*** weakness:
  - Backing up the phone copies all the data off in a form not encrypted using the in-chip secret
    - After all, you need to be able to recover it onto a new phone!
- So someone who can get your phone...
  And can somehow managed to have it unlocked
  - Thief, abusive boyfriend, cop...
    - Hold it up to your face (iPhone X) or Fingerprint (5s or beyond)
    - And then sync it with a new computer
- Change of policy for iOS-11:
  - Now you also need to put in the passcode to trust a new computer:
    Can't create a backup without knowing the passcode

But A Lot More Uses for Random Numbers...

- The key foundation for all modern cryptographic systems is often not encryption but these "random" numbers!
- So many times you need to get something random:
  - A random cryptographic key
  - A random initialization vector
  - A "nonce" (use-once item)
  - A unique identifier
  - Stream Ciphers
- If an attacker can ***predict*** a random number things can catastrophically fail

Breaking Slot Machines

- Some casinos experienced unusual bad "luck"
  - The suspicious players would wait and then all of a sudden try to play
- The slot machines have ***predictable*** pRNG
  - Which was based on the current time & a seed
- So play a little...
  - With a cellphone watching
  - And now you know when to press "spin" to be more likely to win
- Oh, and this ***never*** effected Vegas!
  - ***Evaluation standards*** for Nevada slot machines specifically designed to address this sort of issue



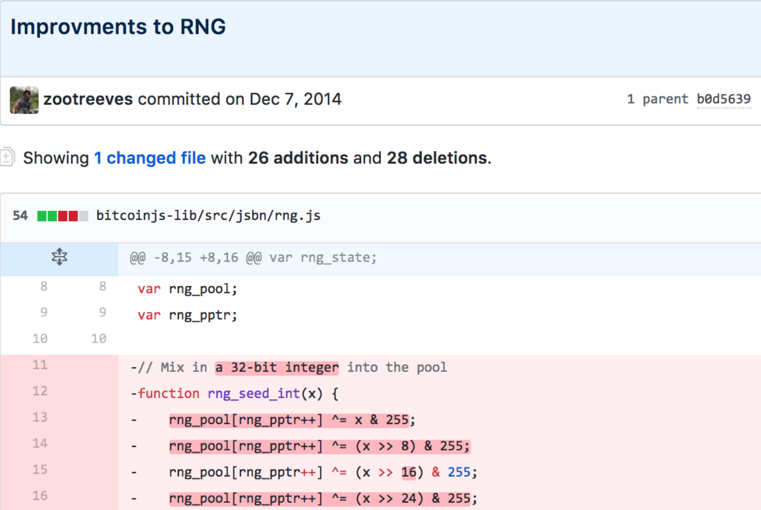
BRENDAN KOERNER SECURITY 02.06.17 07:00 AM

RUSSIANS ENGINEER A BRILLIANT SLOT MACHINE

IN EARLY JUNE 2014, accountants at the Lumiere Place Casino in St. Louis noticed that several of their slot machines had—just for a couple of days—gone haywire. The government-approved software that powers such machines gives the house a fixed mathematical edge, so that casinos can be certain of how much they'll earn over the long haul—say, 7.129 cents for every dollar played. But on June 2 and 3, a number of Lumiere's machines had spit out far more money than they'd consumed, despite not awarding any major jackpots, an aberration known in industry parlance as a

Breaking Bitcoin Wallets

- blockchain.info supports "web wallets"
  - Javascript that protects your Bitcoin
- The private key for Bitcoin needs to be random
  - Because otherwise an attacker can spend the money
- An "Improvment" [sic] to the RNG reduced the entropy (the actual randomness)
  - Any wallet created with this improvment was brute-forceable and could be stolen



Improvments to RNG

zootreeves committed on Dec 7, 2014 1 parent b0d5639

Showing 1 changed file with **26 additions** and **28 deletions**.

54 🟩🟩🟥🟥 bitcoinjs-lib/src/jsbn/rng.js

```
@@ -8,15 +8,16 @@ var rng_state;
 var rng_pool;
 var rng_pptr;

-// Mix in a 32-bit integer into the pool
-function rng_seed_int(x) {
-    rng_pool[rng_pptr++] ^= x & 255;
-    rng_pool[rng_pptr++] ^= (x >> 8) & 255;
-    rng_pool[rng_pptr++] ^= (x >> 16) & 255;
-    rng_pool[rng_pptr++] ^= (x >> 24) & 255;
```

TRUE Random Numbers

- True random numbers generally require a physical process
- Common circuit is an unusable ring oscillator built into the CPU
    - It is then sampled at a low rate to generate true random bits which are then fed into a pRNG on the CPU
- Other common sources are human activity measured at very fine time scales
    - Keystroke timing, mouse movements, etc
        - "Wiggle the mouse to generate entropy for a key"
    - Network/disk activity which is often human driven
- More exotic ones are possible:
    - Cloudflare has a wall of lava lamps that are recorded by a HD video camera which views the lamps through a rotating prism: It is just one source of the randomness

Combining Entropy

- The general procedure is to combine various sources of entropy
- The goal is to be able to take multiple crappy sources of entropy
    - Measured in how many bits:
      A single flip of a coin is 1 bit of entropy
    - And combine into a value where the entropy is the minimum of the sum of all entropy sources (maxed out by the # of bits in the hash function itself)
    - **N-1** bad sources and **1** good source -> good pRNG state

Pseudo Random Number Generators (aka Deterministic Random Bit Generators)

- Unfortunately one needs a ***lot*** of random numbers in cryptography
  - More than one can generally get by just using the physical entropy source
- Enter the pRNG or DRBG
  - If one knows the state it is entirely predictable
  - If one doesn't know the state it should be indistinguishable from a random string
- Three operations
  - Instantiate: (aka Seed) Set the internal state based on the real entropy sources
  - Reseed: Update the internal state based on both the previous state and ***additional entropy***
    - The big different from a simple stream cipher
  - Generate: Generate a series of random bits based on the internal state
    - Generate can also optionally add in additional entropy
- **instantiate(entropy)**
  reseed(entropy)
  generate(bits, {optional entropy})

Properties for the pRNG

- Can a pRNG be truly random?
  - No. For seed length **s**, it can only generate at most **2^s** distinct possible sequences.
- A cryptographically strong pRNG "looks" truly random to an attacker
  - Attacker ***cannot distinguish*** it from a random sequence:
    If the attacker can tell a sufficiently long bitstream was generated by the pRNG instead of a truly random source it isn't a good pRNG

Prediction and Rollback Resistance

- A pRNG should be predictable only if you know the internal state
  - It is this predictability which is why its called "pseudo"
- If the attacker does not know the internal state
  - The attacker should not be able to distinguish a truly random string from one generated by the pRNG
- It should also be rollback-resistant
  - Even if the attacker finds out the state at time T, they should not be able to determine what the state was at T-1
  - More precisely, if presented with two random strings, one truly random and one generated by the pRNG at time T-1, the attacker should not be able to distinguish between the two

Why "Rollback Resistance" is Essential

- Assume attacker, at time T, is able to obtain all the internal state of the pRNG
  - How? E.g. the pRNG screwed up and instead of an IV, released the internal state, or the pRNG is bad...
- Attacker observes how the pRNG was used
  - T_{-1} = Session key
    T_0 = Nonce
- Now if the pRNG doesn't resist rollback, and the attacker gets the state at T_0, attacker can know the session key! And we are back to...

More on Seeding and Reseeding

- Seeding should take all the different physical entropy sources available
  - If one source has 0 entropy, it ***must not*** reduce the entropy of the seed
  - We can shove a whole bunch of low-entropy sources together and create a high-entropy seed
- Reseeding ***adds*** in even more entropy
  - **F(internal_state, new material)**
  - Again, even if reseeding with 0 entropy, it ***must not*** reduce the entropy of the seed

Probably the best pRNG/DRBG: HMAC_DRBG

- Generally believed to be the best
  - ***Accept no substitutes***!
- Two internal state registers, ***V*** and ***K***
  - Each the same size as the hash function's output
- ***V*** is used as (part of) the data input into HMAC, while ***K*** is the key
- If you can break this pRNG you can ***either break the underlying hash function*** or ***break a significant assumption about how HMAC works***
  - Yes, security proofs sometimes are a very good thing and actually do work

HMAC_DRBG
Generate

- The basic generation function
- Remarks:
  - It requires one HMAC call per blocksize-bits of state
  - Then two more HMAC calls to update the internal state
- Prediction resistance:
  - If you can distinguish new **K** from random when you don't know old **K**:
    You've distinguished HMAC from a random function!
    Which means you've either broken the hash or the HMAC construction
- Rollback resistance:
  - If you can learn old **K** from new **K** and **V**:
    You've reversed the hash function!

```
function hmac_drbg_generate (state, n) {
  tmp = ""
  while(len(tmp) < N){
     state.v = hmac(state.k,state.v)
     tmp = tmp || state.v
  }
  // Update state with no input
  state.k = hmac(state.k, state.v || 0x00)
  state.v = hmac(state.k, state.v)
  // Return the first N bits of tmp
  return tmp[0:N]
}
```

HMAC_DRBG Update

- Used instead of the "no-input update" when you have additional entropy on the generate call
- Used standalone for both instantiate (**state.k = state.v = 0**) and reseed (keep **state.k** and **state.v**)
- Designed so that even if the attacker controls the input but doesn't know **k**:
  The attacker should not be able to predict the new **k**

```
function hmac_drbg_update (state, input) {
  state.k = hmac(state.k, state.v || 0x00
                                  || input)
  state.v = hmac(state.k, state.v)
  state.k = hmac(state.k, state.v || 0x01
                                  || input)
  state.v = hmac(state.k, state.v)
}
```

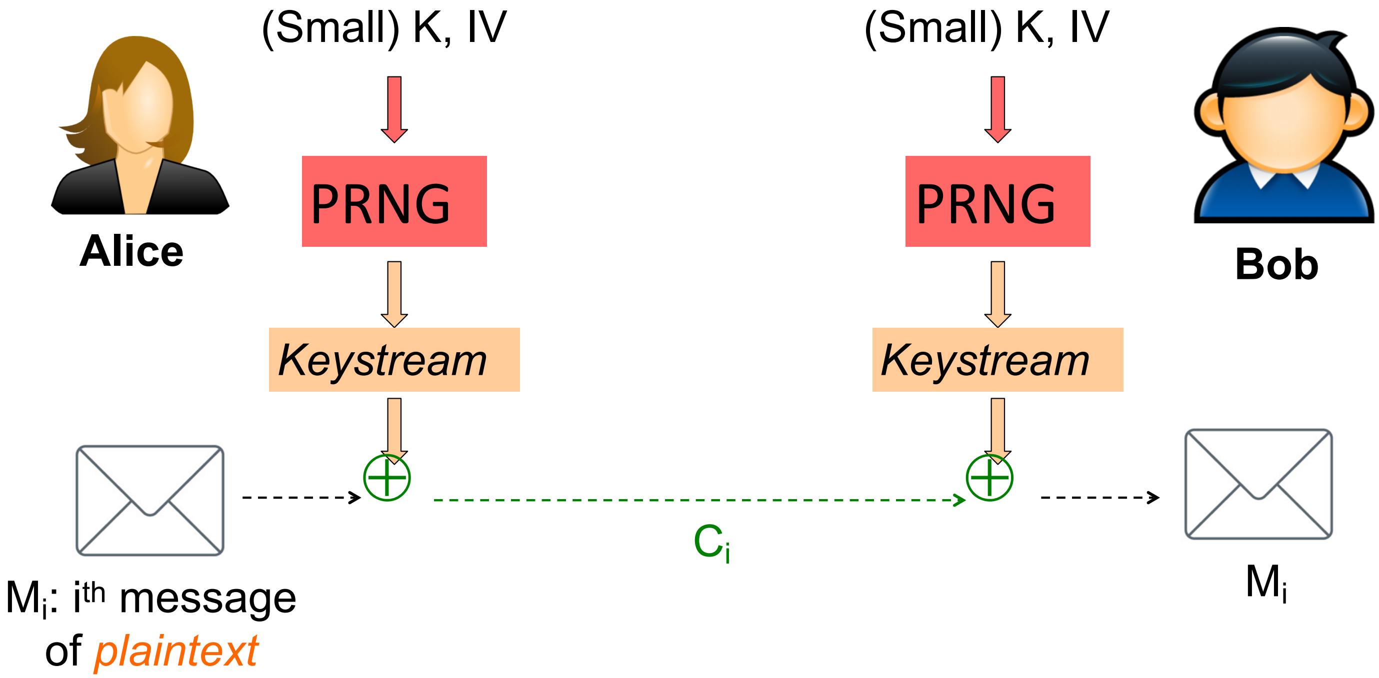
Stream ciphers

- Block cipher: fixed-size, stateless, requires “modes” to securely process longer messages
- Stream cipher: keeps state from processing past message elements, can continually process new elements
- Common approach: “one-time pad on the cheap”:
  - XORs the plaintext with some “random” bits
- But: random bits ≠ the key (as in one-time pad)
  - Instead: output from cryptographically strong pseudorandom number generator (pRNG)
  - Anyone who actually calls this a "One Time Pad" is selling snake oil!

Building Stream Ciphers

- Encryption, given key **K** and message **M**:
  - Choose a random value IV
  - **E(M, K)** = **pRNG(K, IV)** ⊕ **M**
- Decryption, given key **K**, ciphertext **C**, and initialization vector **IV**:
  - **D(C, K) = PRNG(K, IV)** ⊕ **C**
- Can encrypt message of any length because pRNG can produce any number of random bits...
  - But in practice, for an n-bit seed pRNG, stop at $\mathbf{2}^{n/2}$. Because, of course...

Using a PRNG to Build a Stream Cipher



CTR mode is (mostly) a stream cipher

- **E(ctr,K)** should look like a series of pseudo random numbers...
  - But after a large amount it is ***slightly*** distinguishable!
- Since it is actually a pseudo-random ***permutation***...
  - For a cipher using 128b blocks, you will never get the same 128b number until you go all the way through the 2^{128} possible entries on the counter
  - Reason why you want to stop after 2^{64}
    - if you are foolish enough to use CTR mode in the first place
- Also very minor information leakage:
  - If $\mathbf{C_i} = \mathbf{C_j}$, for **i != j**, it follows that $\mathbf{M_i}$ **!=** $\mathbf{M_j}$

UUID: Universally Unique Identifiers

- You got to have a "name" for something...
  - EG, to store a location in a filesystem
- Your name ***must*** be unique...
  - And your name ***must*** be unpredictable!
- Just chose a ***random*** value!
  - UUID: just chose a 128b random value
    - Well, it ends up being a 122b random value with some signaling information
  - A good UUID library uses a cryptographically-secure pRNG that is properly seeded
- Often written out in hex as:
  - 00112233-4455-6677-8899-aabbccddeeff

What Happens When The Random Numbers Goes Wrong...

- Insufficient Entropy:
  - Random number generator is seeded without enough entropy
- Debian OpenSSL CVE-2008-0166
  - In "cleaning up" OpenSSL (Debian 'bug' #363516), the author 'fixed' how OpenSSL seeds random numbers
    - Because the code, as written, caused Purify and Valgrind to complain about reading uninitialized memory
  - Unfortunate cleanup reduced the pRNG's seed to be ***just*** the process ID
    - So the pRNG would only start at one of ~30,000 starting points
- This made it easy to find private keys
  - Simply set to each possible starting point and generate a few private keys
  - See if you then find the corresponding public keys anywhere on the Internet

http://blog.dieweltistgarnichtso.net/Caprica,-2-years-ago

And Now Lets
Add Some RNG Sabotage...

- The Dual_EC_DRBG
  - A pRNG pushed by the NSA behind the scenes based on Elliptic Curves
- It relies on two parameters, ***P*** and ***Q*** on an elliptic curve
  - The person who generates ***P*** and selects ***Q=eP*** can predict the random number generator, regardless of the internal state
- It also ***sucked!***
  - It was horribly slow and even had subtle biases that shouldn't exist in a pRNG: You could distinguish the upper bits from random!
- Now this was spotted fairly early on...
  - Why should anyone use such a horrible random number generator?

Well, anyone not paid that is...

- RSA Data Security accepted ~~30 pieces of silver~~ $10M from the NSA to implement Dual_EC in their RSA BSAFE library
  - And ***silently*** make it the default pRNG
- Using RSA's support, it became a NIST standard
  - And inserted into other products...
- And then the Snowden revelations
  - The initial discussion of this sabotage in the NY Times just vaguely referred to a Crypto talk given by Microsoft people...
    - That everybody quickly realized referred to Dual_EC

But this is insanely powerful...

- It isn't just forward prediction but being able to run the generator backwards!
  - Which is why Dual_EC is so nasty:
    Even if you know the internal state of HMAC_DRBG it has rollback resistance!
- In TLS (HTTPS) and Virtual Private Networks you have a motif of:
  - Generate a random session key
  - Generate some other random data that's ***public visible***
    - EG, the IV in the encrypted channel, or the "random" nonce in TLS
    - Oh, and an NSA sponsored "standard" to spit out even more "random" bits!
- If you can run the random number generator ***backwards***, you can find the session key

It Got Worse:
Sabotaging Juniper

- Juniper also used Dual_EC in their Virtual Private Networks
    - "But we did it safely, we used a different **Q**"
- Sometime later, someone else noticed this...
    - "Hmm, **P** and **Q** are the keys to the backdoor...
      Lets just hack Juniper and rekey the lock!"
        - And whoever put in the first Dual_EC then went "Oh crap, we got locked out but we can't do anything about it!"
- Sometime later, someone else goes...
    - "Hey, lets add an ssh backdoor"
- Sometime later, Juniper goes
    - "Whoops, someone added an ssh backdoor, lets see what else got F'ed with, oh, this # in the pRNG"
- And then everyone else went
    - "Ohh, patch for a backdoor. Lets see what got fixed. Oh, these look like Dual_EC parameters..."

Sabotaging "Magic Numbers" In General

- Many cryptographic implementations depend on "magic" numbers
  - Parameters of an Elliptic curve
  - Magic points like ***P*** and ***Q***
  - Particular prime ***p*** for Diffie/Hellman
  - The content of S-boxes in block cyphers
- Good systems should cleanly describe how they are generated
  - In some sound manner (e.g. AES's S-boxes)
  - In some "random" manner defined by a pRNG with a specific seed
    - Eg, seeded with "Nicholas Weaver Deserves Perfect Student Reviews"...
      Needs to be very low entropy so the designer can't try a gazillion seeds

Because Otherwise You Have Trouble...

- Not only Dual-EC's ***P*** and ***Q***
- Recent work: 1024b Diffie/Hellman moderately impractical...
  - But you can create a sabotaged prime that is 1/1,000,000 the work to crack!
    And the most often used "example" ***p***'s origin is lost in time!
- It can cast doubt ***even when a design is solid***:
  - The DES standard was developed by IBM but with input from the NSA
    - Everyone was suspicious about the NSA tampering with the S-boxes...
    - They did: The NSA made them ***stronger*** against an attack they knew but the public didn't
  - The NSA-defined elliptic curves P-256 and P-384
    - I trust them because they are in Suite-B/CNSA so the NSA uses them for TS communication:
      A backdoor here would be absolutely unacceptable...
      but ***only because I actually believe the NSA wouldn't go and try to shoot itself in the head!***

So What To Use?

- AES-128-CFB or AES-256-CFB:
  - Robust to screwups encryption
- SHA-2 or SHA-3 family (256b, 384b, or 512b):
  - Robust cryptographic hashes, SHA-1 and MD5 are broken
- HMAC-SHA256 or HMAC-SHA3:
  - Different function than the encryption:
    Prevents screwups on using the same key & is a hash
  - Always Encrypt Then MAC!
- HMAC-SHA256-DRBG or HMAC-SHA3-DRBG:
  - The best pRNG available